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ULTRA-LIGHT DUCT FOR AN ANECHOIC WIND TUNNEL

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Summary

A tunnel ultra-light (or TUL) is a duct composed of acoustically transparent cloth designed to transform an open-jet wind tunnel into a closed-jet wind tunnel. This concept is of interest (a priori) for anechoic wind tunnels because it improves the aerodynamic quality without hindering the measurement of sound in the far field.

The present document describes a full scale device designed for the 3 m diameter test section of CEPRA 19. The apparatus installation did not develop any significant problems and the mechanical support turned out to be excellent. Aerodynamic and acoustic tests are discussed. The study revealed certain imperfections in the installation as tested - instabilities above 25 m/s and acceptable cloth transmission up to 4 kHz only.

The conclusions are that the system as tested could eventually be used in certain applications, for example, in ground based transport. However, the concept of TUL must be developed further to arrive at a reliable mechanism for use in a large number of applications.

NOTATION

A	acoustic attenuation of the TUL, dB
C_p	pressure coefficient, $(p_s-p_o)/(P_{io}-p_o)$
f	acoustic frequency, Hz
f_c	center frequency of a third octave band, Hz

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h	distance from the measurement point to the TUL wall, mm
Kp	pressure coefficient of the sphere, $(p_{sphere}-p_o)/(P_{io}-p_o)$
L	sound pressure level, ref $2x10^{-5}$ Pa
P_{io}	reference total pressure measured at the nozzle inlet, Pa
p_s	static pressure on the interior wall of the TUL, Pa
p_{sphere}	static pressure in the sphere, Pa
p_o	reference static pressure measured in the plane of the nozzle, Pa
T	axial restraining force on the TUL, daN
V_t	flow speed in the TUL (out of the boundary layer), m/s
V_o	flow speed in the plane of the nozzle, m/s
X	distance from the measurement point to the nozzle plane, m
δ_1	boundary-layer displacement thickness, mm
Δp	pressure difference created by the venturi, p_o-p_{sphere}
ΔZ	vertical displacement of the lower section of the TUL at $X = 5$ m with respect to its position at very low speed ($V_o = 2$ to 6 m/s), mm
θ	radiation angle of the sound field ($\theta = 0°$ downstream), deg
τ	acoustic transmission coefficient of the TUL, $= 10^{-A/10}$
φ_v	venturi exit diameter, m
φ_o	nozzle diameter (3m)

INTRODUCTION

Anechoic wind tunnels are designed to permit the measurement of far field noise of models. This fundamental characteristic implies that the flow must be produced by an open jet of long length. This creates a mixing layer surrounding the potential core. The mixing layer causes two unfortunate effects: first, complex refraction corrections must be introduced to account for sound transmission through the turbulent region, and second, the volume of the clean potential flow is limited, which restricts the size and position of the models. Furthermore, recirculation in the anechoic chamber created by the shear layer perturbs the acoustic field at low frequencies.

It is in this context that the idea of the ultra-light test section (TUL) was conceived. The concept is to constrain the free jet in a duct formed from porous cloth that is acoustically transparent. The flow would then possess the same qualities as the flow in a closed-jet test section, that is, a flow with low turbulence and a thin boundary layer. This concept was validated aerodynamically with a model in 1984 [1]. Following these excellent results, it was decided to design a full scale device for the CEPRA 19 anechoic wind tunnel employing the 3 m diameter nozzle.

Several problems were encountered in this study because results from the preceding tests with a 8/100 scale model could not be extrapolated simply. Consequently, the total mass of the cloth is significantly greater than anticipated and the intermediate supports must be avoided. In addition, it was necessary to select, at the conclusion of the preliminary tests which were necessarily incomplete, a cloth with a certain number of mechanical and aerodynamic specifications and yet have adequate acoustic transmission properties.

The tests were conducted in January and February, 1988. The present report describes the device that was fabricated and its installation in the wind tunnel, as well as the modifications which tended to improve the stability of the TUL. The aerodynamic and acoustic measurements, which were made under laboratory conditions, are presented. The results lead to conclusions that will enable us to plan a future program of system development.

1. INSTALLATION AND MECHANICAL PERFORMANCE OF THE TUL

1.1 Installation in CEPRA 19

The general schematic of the TUL in CEPRA 19 and the separate components of the device are presented in figure 1. The wind tunnel, designed by ONERA, had been fabricated and installed by the AMCI Company.

The principle of the device set up is as follows. A hoop, equipped with a zipper, is attached to the test section nozzle. A similar hoop, equipped with a zipper on one side and a venturi on the other, is positioned in the diffuser entrance by means of a vertical winch. The cloth tube, with 3 m diameter and a length of 12 m, is connected to the upstream and downstream hoops by the zippers. Rings in the cloth suspended from a horizontal cable above the TUL help in the tube installation and support the weight of the cloth at regular intervals. The TUL has another zipper along the bottom for the purpose of installing the support strut and model, an acoustic source, or other instrumentation into the tube. Finally, an axial force is transferred to the downstream hoop with the aid of a shroud, which gives the TUL its cylindrical form.

This installation of the TUL in CEPRA 19 did not cause any significant problems.

1.2 Operation of the venturi

The venturi, created by the decrease in cross sectional area at the duct exhaust, must create a pressure difference ΔP between the interior and exterior of the TUL. The ΔP must be sufficient to stop the cloth from flapping yet be small enough to avoid excessive loads in the TUL (ΔP was limited to 200 Pa in these tests). Thus, the venturi is an essential element in the TUL and the first series of tests were aimed at understanding the venturi's effects on the shape and stability of the cloth duct.

The venturi, initially planned to be cloth, created an excessive pressure differential, even at very low speeds in the duct, because its shape was too convergent at its downstream end. It was necessary to replace the venturi with one having an exhaust diameter, $\varphi_v = 2.905$ m, and then, by making foam venturis from extruded polystyrene, to test venturis with successive exhaust diameters of 2.67 m, 2.745 m, and 2.84 m.

The measured values of ΔP for different diameters, φ_v, as a function of the flow speed, V_0 (figure 2), are much greater than would be predicted simply from the ratio of the diameters φ_v/φ_0. This shows that it is important to account for the boundary-layer thickness δ_1 just upstream of the venturi to correctly predict ΔP. The calculation of ΔP, taking account of the cloth porosity, is in good agreement with measurements.

Moreover, these venturi tests verified that a venturi with a small exhaust diameter, which results in a significant ΔP for a given speed V_0, tends to improve the stability of the TUL. Associated with the tests of the restraining force T, they also allowed studies of the duct deformation.

1.3 Deformations of the TUL

The increase of airspeed in the test section was accompanied by an increase of the pressure differential ΔP and, consequently, by an enlargement of the cloth tube. The growth of the perimeter of the TUL, measured at X = 5 m and proportional to ΔP (1 mm/Pa), is greater than that predicted by the small scale tests (0.35 mm/Pa).

Associated with this enlargement was a curvature of the duct into the shape of a banana visible in figure 3. Compared to the threshold position with the tube collapsed (ΔZ = - 60 mm), this curvature is considerably accentuated by the speed V_0. The curvature sometimes leads to an impressive instability mode because of an inversion of the static pressure $p_s - p_{sphere}$ at the end of the TUL coupled with a violent local constriction. It should be noted that the assembly, especially the cloth, the seams and zippers, are exactly resistant to the large forces existing during these episodes.

In an attempt to understand the causes of the curvature, a test was made with the downstream hoop lowered from 190 mm, but the behavior of the duct was not modified. Only an increase in the restraining force T (increased from 60 daN to 140 daN) noticeably reduced the phenomenon.

These studies have not yet led to an explanation of the behavior of the complete TUL, in particular the growth of curvature in the shape of a banana during the increase in airspeed and the important hysteresis of the duct deformations. It is however established that a venturi with a small cross section and a large restraining force create the most stable installation. It is under these conditions that the aerodynamic and acoustic measurements were made.

2. AERODYNAMIC TESTS

2.1. Static pressure at the wall of the TUL

The internal static pressure p_S of the TUL was measured using pressure orifices glued to the cloth along the duct. Except close to the venturi, the static pressure is uniform in a given cross section X of the TUL. The speed V_t (outside the boundary layer) in this section X can be linked to the pressure coefficient C_p by the simple relationship:

$$(V_t / V_o)^2 = 1 - C_p \qquad\qquad (C_p > 0 \Leftrightarrow V_t < V_o).$$

It must be emphasized that the difficulty of attaching the pressure ports to the cloth and measuring the very weak pressure differentials $p_S - p_0$ (from a few Pa to several tens of Pa) makes the use of these measurements nebulous. Nevertheless, we could verify that the increase in airspeed V_0 or the decrease in diameter φ_V of the venturi, which reduces the pressure in the anechoic room and increases the cross section of the TUL (by air injection), tends to reduce the ratio V_t / V_0.

Moreover, we observed at the end of the TUL the influence of the proximity of the venturi. In effect, on approaching the venturi the static pressure does not remain uniform; it deforms. This pressure gradient causes an acceleration of the flow in the center of the tube and a deceleration of the flow close to the wall. The closest pressure orifice to the venturi measured this deceleration, which becomes more pronounced when the change in venturi cross section becomes greater.

Finally, the airspeed V_t seemed to change little along the TUL and stayed close to the speed V_0 at the duct entrance.

2.2 Internal flow

Surveys of the internal flow were made with the aid of a Pitot probe in the lower part of the duct, at X = 5 m from the nozzle and then just upstream of the venturi. The average velocity profiles were calculated from the total and static pressures acquired at each measurement point.

In the cross section X = 5 m (figure 4), and outside the boundary layer, whose displacement thickness δ_1 is of the order of 25 mm, the airspeed V_t is slightly less (by several per cent) than the airspeed V_o at the nozzle exit. This agrees with the static pressures measured on the wall of the TUL ($C_p > 0$) and with a calculation that, taking into account the expected duct expansion, the cloth porosity, and the boundary-layer thickness δ_1 for $V_o = 15$ and 20 m/s, respectively, predicted the airspeed deficits of 1.5% and 4 %. In the plane of the survey upstream of the venturi, the velocity field is deformed because of the proximity of the venturi, and the boundary-layer thickness is appreciably greater than that in the preceding cross section.

Thus, these measurements show that suction of the boundary layer is limited to a value determined by the cloth porosity (along the length of the TUL, δ_1 tends asymptotically to a value less than 1 mm). It is possible that the large boundary-layer thickness, that tends to cause the pressure at the end of the TUL to drop, contributes to the instability of the system. A more porous cloth than that used would actually result in suction off of the boundary layer, and would be an additional factor in the stability.

3. ACOUSTIC TESTS

3.1. Experimental method

This phase of the study of the TUL is equally important because the selection of the cloth, as far as the acoustic criteria are concerned, could only be made based on incomplete results using a Kundt tube. Thus, the preliminary experiments were limited to normal incident waves without flow. Furthermore, as it was desirable to utilize samples with a sufficient dimension (10 cm diameter), the measurements were only made up to 1700 Hz.

In CEPRA 19, four flow speeds were selected, which covered the correct range of the TUL: $V_o = 0$, 12, 15, and 20 m/s. In each case, the following configurations were employed:

- background noise (except at $V_o = 0$) with the noise source in place, plus some data points with an empty test section and with the TUL installed;

- noise source driven by white noise filtered in the band 0.9 to 22.5 kHz, which allows analysis of the 14 third octaves with center frequencies $f_c = 1$ to 20 kHz;

- noise source driven sinusoidally at a fairly high frequency which is $f = 6.3$ kHz, corresponding to a third-octave center frequency.

The electro-acoustic source is made from a JBL 2420 compression driver placed in an ellipsoidal aerodynamic body and mounted in the center of the anechoic sphere; the acoustic opening is lateral at $\theta = 90°$. The excitation is fixed at 5 V_{eff}. All the tests were made with the moving microphone (Bruel and Kjaer 1/4 inch) in the anechoic chamber in the horizontal plane of the sphere diameter and 6 m from the source (the cloth has no longitudinal seams in this plane between the sound and the observation area). The measurements were made by the CEPr at 24 positions from $\theta = 30°$ to $\theta = 145°$ every 5° ($\theta = 0°$ is downstream in the wind tunnel).

3.2. General aspects of the measurements

Figure 5 summarizes some typical results for a speed of 20 m/s. The source was driven by white noise. The data curves are limited to five third octaves for which the center frequencies coincide with octaves (f_c = 1, 2, 4, 8, and 16 kHz). The first column corresponds to the directivity measured in free field and the second to that found with the TUL in place. The last shows the attenuation caused by the TUL, which is the difference between the two preceding curves. Note that the vertical scale of the last column is expanded to twice the sensitivity of the preceding ones (5 dB increments instead of 10 dB). As expected, the source directivity is greatest at high frequencies. Apparently, the fall off at the sides ($\theta < 60°$ and $\theta > 120°$) is less in the presence of the TUL. That is a result of the fact that the maximum attenuation seems to occur at $\theta = 90°$, contrary to anticipations. A simple model can explain the origin of this phenomenon - at high frequencies the transmission $\tau = 10^{-A/10}$ is weak, so that the waves are reflected in the TUL interior and contribute in a negligible manner to the lateral radiation. The calculations that were made correctly predict the measured effect.

When the source is excited by a pure frequency of 6300 Hz, the curves fluctuate greater than with white noise, especially with the TUL. This is easily explained: for a broad band emission, the analysis creates an average of the frequencies in each third octave, which has a tendency to blur the variations caused by imperfections in the anechoic chamber and variations caused by the interferences from reflections in the TUL. Effectively, if the measured results are smooth they correspond exactly to those obtained with white noise in a third octave band centered at f_c = 6300 Hz.

3.3 Synthesis of results

It was indicated that only for normal incidence has the attenuation, A, a physical significance. The calculation shows that the exact value can be under valued by around 0.5 dB, which is small. Consequently, a synthesis of the results is undertaken only for measurements at $\theta = 90°$.

Concerning the accuracy of the tests, certain points were repeated at a minimum of one week interval; the spread of the results remained less than 1 dB. For the background noise found in the anechoic chamber, a general law tends to develop (figure 6): it is weaker with the TUL and the difference grows with airspeed, always staying below 3 dB in most cases. This can be explained by the fact that the closed jet is calmer and, consequently, quieter than the open jet, as well as by the suppression of recirculation. It is, however, possible that the improvement is only apparent and is created by the attenuation of internal noise as it transmits across the TUL. The observed variations are too weak to allow an unambiguous conclusion; the experiments at high speed, when that will be possible, will result in a better answer.

Figure 7 gives the principle result of the acoustic study. It shows the attenuation, A, at $\theta = 90°$, deduced from tests with white noise as a function of the third-octave center frequencies, f_c. In the range of low speeds V_0 explored, no flow effect showed itself since all the data points are closely grouped around an average curve within + or - 0.5 dB. This is confirmed in figure 8 where all values of A, in the band f_c = 6300 Hz, are correlated with V_0 equally well for white noise as for a pure tone. In the second case, the variations are greater because of the fluctuations of the attenuation curves. In any case, there is no systematic correspondence with V_0.

Figure 7 confirms the tests of the samples in the Kundt tube - in effect, the transmission τ up to 1700 Hz (first three third octaves) is greater than 0.6, so that $A = 10 \log (1/\tau) < 2.2$ dB. However, the attenuation grows linearly on the graph above 2 kHz and attains a value around 13 dB in the range 12.5 to 20 kHz. This value is very high since it corresponds to τ = 5% only. The calculation shows that the directivity of the radiated noise is thereby profoundly modified by the contribution from waves reflected by the walls of the TUL, which is not acceptable. It follows from figure 7 that the attenuation can be judged acceptable only up to 4 kHz. It is therefore necessary to continue the search for a cloth which possesses the required mechanical and aerodynamic requirements and for which the transmission remains satisfactory to 10 kHz.

CONCLUSION

The tests of an ultra-light tunnel, or TUL, in the CEPRA 19 anechoic wind tunnel were found to be very instructive because they uncovered a certain number of differences with respect to the predictions and small scale model studies. It is evident that the development is more difficult than was estimated in the beginning.

The first tests showed that the pressure difference between the interior and exterior of the TUL is greater than that anticipated. Several modifications were made to the venturi that resulted in improved stability of the TUL. It was not possible, however, to achieve proper performance at speeds above 25 m/s.

The aerodynamic measurements verified that the longitudinal and transverse evolution of airspeed in the TUL are similar to those in a closed jet. They showed that a large restraining force and a venturi with small cross section are the stabilizing factors, but they did not explain all the behavior of the TUL beyond 25 m/s. Nevertheless, these experiments generated the information necessary to better predict the venturi efficiency.

The acoustic study uncovered a modification of the sound radiation directivity from sources located in the duct caused by reflections from the cloth. This effect was confirmed by a simple calculation. It led to a limit to the allowable attenuation during transmission across the covering. The transmission could not be measured previously except with samples and only at low frequencies. The present results confirm that the transmission is good. On the other hand, it decreased strongly at high frequencies, which conflicts with most research requirements for pass bands to 10 kHz.

Finally, the work uncovered several positive elements such as the mounting ease and solidity, the good aerodynamic characteristics at low speeds, and an acoustic transmission that was acceptable to around 4 kHz. These points could lead to future use of the TUL system in CEPRA 19 for certain applications such as in the area of ground based transport. However, further work is needed before the TUL can be used in a systematic and reliable manner. One aspect of the research should be aimed at the causes of the instability, so that proper operation could be achieved through the entire practical speed range, which is to say to 50 m/s. Also, it is probable that a more porous cloth would improve both suction of the boundary layer and high frequency acoustic transmission. The concept is sufficiently interesting that it merits further effort. Another test in CEPRA 19 is

envisioned with a modified system, which would take into account the new ideas that have just been expressed.

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